

Tropical Cyclone Intensity and Structure: Improved Understanding and Prediction. Evaluation of Existing and Development of New Techniques for Global and Mesoscale NWP Model Assessment

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Grant Number: N00014-021-1-0181

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LONG-TERM GOALS

This is the first year of a new grant. As such, I will briefly re-state the long-term goals. I am continuing research from my previous ONR grant on estimating the theoretical limits to tropical cyclone *track* errors, but with an emphasis now on distinguishing between overall track errors, and position and timing errors at landfall. My previous ONR grant showed a potential further halving of the mean absolute track errors over the major tropical cyclone (TC) basins. Because of the increased complexity, this error reduction is most likely to be even greater for TCs nearing or making landfall, so track error reduction will continue as a long-term goal. My second goal is to use both similar and new techniques to estimating the predictability limits of tropical cyclone *intensity* and *intensity change* out to at least 96 hours. Given that identified that there remain large errors in TC prediction, my third goal is to identify, quantify and reduce these sources of errors. My fourth goal is to improve the initial state specification for TCs by continuing the development and application of 4D data assimilation procedures, particularly with respect to the ingestion of newly emerging data sources. Model development also will continue throughout the period of the grant as such development is vital for improved predictions. I note here that for the third and fourth goals, special emphasis again will be placed on landfalling tropical cyclones, as they are the most destructive storms. My fifth, and final, goal is to address the crucial question of how best to assess NWP model forecast skill. The above goals all have significant implications for transitions.

OBJECTIVES

My first two scientific objectives are to finalize, over the period of the grant, work on estimating the intrinsic limits of predictability of tropical cyclone (TC) mean forecast position errors and of tropical cyclone intensity errors. These intrinsic limits of predictability for TCs exist because the equations governing the behavior of atmospheric systems, including TCs, are deterministically chaotic. Errors in the initial conditions, model formulation and boundary conditions lead to error growth that eventually swamps the skill of the forecasts and eventually they lose all skill. The first two objectives are link directly to the third. I am carrying out an extensive research program, directed at identifying and understanding the sources of errors in both the initial conditions and the model formulation, and to reducing these errors. This third objective forms the major part of the research program of numerical analysis and prediction in this proposal. I note that my focus will be largely, but not exclusively, on TCs that are approaching or making landfall, as they are the most devastating in terms of loss of life, and property. The fourth objective is the continued development of my 4D-VAR data assimilation scheme. It has shown great promise when applied to the first three objectives. I also intended to

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 30 SEP 2002		2. REPORT TYPE		3. DATES COVERED 00-00-2002 to 00-00-2002	
4. TITLE AND SUBTITLE Tropical Cyclone Intensity and Structure: Improved Understanding and Prediction. Evaluation of Existing and Development of New Techniques for Global and Mesoscale NWP Model Assessment				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) School of Mathematics, The University of New, South Wales, Sydney 2052, Australia, , ,				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This is the first year of a new grant. As such, I will briefly re-state the long-term goals. I am continuing research from my previous ONR grant on estimating the theoretical limits to tropical cyclone track errors, but with an emphasis now on distinguishing between overall track errors, and position and timing errors at landfall. My previous ONR grant showed a potential further halving of the mean absolute track errors over the major tropical cyclone (TC) basins. Because of the increased complexity, this error reduction is most likely to be even greater for TCs nearing or making landfall, so track error reduction will continue as a long-term goal. My second goal is to use both similar and new techniques to estimating the predictability limits of tropical cyclone intensity and intensity change out to at least 96 hours.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

improve upon the 4D-VAR scheme, especially its efficiency and its ability to ingest the many emerging data sources such as the satellite and radar data. Finally, my fifth objective is to evaluate existing schemes for assessing NWP model performance, and to develop alternative procedures. Many of the present methods of model forecast assessment are no longer acceptable as they frequently are biased towards the NWP models. The S1 skill score has been the standard measure of skill in NWP and a score of 20 or below is regarded as a perfect forecast. Presently, most NWP models are registering long term mean S1 scores below 20 out to 36 hours at SLP and out to 48 hours at 500hPa. That the models are not perfect even at 24 hours is easily shown by using simple independent measures of skill. In particular, new assessment schemes are required for TC model forecasts, as they are not well handled by conventional measures of skill. Moreover, emerging procedures such as ensemble forecasting techniques also require a rethinking of assessment procedures.

APPROACH

My approach for each of the five goals is as follows. The methodology employed for the first goal has been explained fully already in the ONR FY00 and FY01 reports and in the literature. This work has involved the use of two very distinct techniques that yielded almost identical answers. The first goal has been to determine how closely the intrinsic predictability limits imposed by the governing equations are currently being approached in practical numerical weather prediction (NWP) models. The practical limits have been improving steadily as the sustained effort in TC track forecast continues at centers around the world. The NWP model I have been using the model was developed at UNSW and is referred to as HIRES. My approach continues to be the generation of an ensemble of initial model states using the archived data sets from various operational global NWP centers around the world. The initial fields generate corresponding ensembles of forecasts at 12 hourly intervals out to 72 hours, after re-setting the TC positions back to their best track locations every 12 hours. The alternative technique, based purely on observational data, was to use a non-linear systems approach to the archived best track data sets. In this case, the spread of initially close pieces of TC trajectories is calculated over a 72 hour period for all available data sets. My second goal, which addresses one of the more difficult and significant problems facing TC research today, is to apply the procedures that proved to be successful in achieving the first goal to the new problem of estimating the predictability characteristics of TC intensity and intensity change. The task is a very large one with the goal again being to calculate predictability limits and how close we are to those in practice. These limits will then be compared for the various TC basins and will again provide information about how close current operational models are to the limits of predictability. The third goal, is to obtain much more realistic TC structure, intensity, intensity change and motion as TCs approach landfall. The third goal links directly with my fourth goal, which is to employ my research program of data assimilation and NWP model prediction to obtain more realistic TC structure and intensity than has been achieved hitherto. Before this work began, I had been producing steadily improving forecasts of TC tracks but had failed to capture the intensity and intensity changes of the TCs. This failure is of extreme importance for TCs at or nearing landfall. The procedure adopted was to use an adjoint sensitivity approach to identify the contributing factors to intensity change and the improvement in the forecasts themselves. In FY02 I have continued to use four dimensional variational assimilation procedures without TC bogussing, taking advantage of high spatial-temporal frequency satellite derived data of various types and as many other sources of data as possible. The approach to the fifth goal is to apply existing measure of assessment of NWP model skill with alternative measures. Initially, the alternative measures will be simple, but will then increase in sophistication as the work proceeds.

WORK COMPLETED

As the grant began just this year, the project is very much work in progress. However, some work has proceeded towards all five objectives. My work on the first goal has focussed on reducing mean track errors for TCs that are regarded as difficult to predict. The findings have been accepted for publication (Leslie and LeMarshall, 2002). I have also extended the work to new basins, including the Bay of Bengal and the south China Sea, in collaboration with the researchers from Indian Meteorological Service, the Chinese Meteorological Agency and the Japan Meteorological Agency. The results are currently being prepared for publication. An example is given in Figure 1 of the RESULTS section, and will be discussed in more detail in that section. My second goal of applying the same procedure to TC intensity predictability has also proceeded, with the emphasis again being on the more difficult storms. This work has produced some intriguing and unexpected results, most notably the large variations from basin to basin. Further development of the HIRES data assimilation and prediction system has proceeded, with the incorporation of new data from radar and satellite sources. This work also has been accepted for publication (Leslie et al. 2002 and LeMarshall and Leslie, 2002). My fourth goal of understanding the contributing factors to, and improving the forecasts of TC intensity and intensity change, especially for landfalling TCs, has yielded early promising results. The primary research tool used in this work has been the continued application of an adjoint sensitivity approach. The procedure enables the impact of selected variables in the initial state to be quantified.

As mentioned in the proposal application, the adjoint sensitivity work recently carried out by the PI and collaborators has shown the existence of precursors with skilful predictability of TC frequency, motion and intensity. These precursors are at very different time scales, ranging from seasonal down to days and even hours. One paper has been published (Leslie et al., 2002) and another has been accepted for publication (Leslie et al., 2002). Thus far, the work has exhibited predictive and understanding capacity for the 1997/98 and 1998/99 seasons in the eastern Indian Ocean basin. Extension to the Pacific and Atlantic TC basins has commenced this year, with two graduate students at the University of Oklahoma working in these areas as the basis of their thesis research. The question of the relative importance of initial /boundary errors and model formulation errors also has arisen during the PI's work in 2001 and has been addressed in joint work with the City University of Hong Kong. A paper has been written and has been accepted for publication (Zhou et al., 2002). This area of research will continue to be pursued as it has implications for predictability, ensemble techniques and other procedures that are based on the assumption that the NWP model either are small compared with initial analysis errors or are not known well enough to be incorporated directly.

RESULTS

I will now describe the main results achieved so far in the first year of this new ONR grant, that is, in FY02. The first set of results relates to the first goal, which was to determine how close current NWP models are to what we believe are the best estimates of the limits of predictability for mean absolute TC track errors. The chaotic nature of the systems and the governing equations results from the non-linearity of the system together with the multifarious feedback processes that take place in such complex systems. The major finding of FY01 was that there is the potential for TC track errors to be *halved*. In FY02 our focus in this grant has shifted in emphasis to TCs nearing or making landfall. Early results for the Atlantic basin, obtained by an OU student employed under this ONR grant, are to be presented at the February 2003 AMS Annual Meeting. They show a significant decrease in model skill, especially for the North and South Carolina coasts. A second set of results concerns the performance of the NWP systems presently at the core of my ONR research program. This model is

the High Resolution (HIRES) data assimilation and prediction system. Largely using ONR support, this system has been developed over a period of more than five years, for use in TC applications by the PI, various graduate students and part-time time research associates. It has continued to undergo development in FY02, especially in the area of data assimilation and representation of cloud microphysics. The HIRES system has been applied to a wide range of problems, as shown clearly in my list of publications attached below. For convenience they are grouped in sections:

TC Motion – the major effort to reduce track errors has been successful, mainly from enhancements in the data base, the 4D data assimilation procedure, the initialization scheme and the model itself. The data base enhancements have come from satellite-derived wind vectors from geostationary satellite cloud and water vapor imagery; from scatterometer winds, Topex-Poseidon analyses of water surface elevation anomalies; radar data; AWS networks; special observing periods and the imminent launching of a new generation of sounders with thousands of channels. An example is shown below for a destructive subtropical cyclone that made landfall in eastern Australian in March 2001. The HIRES model, run with high resolution satellite derived data, at much higher model resolution and with full cloud microphysics, produced forecast tracks, central pressures and rainfall amounts and distributions far superior to those from other NWP centers. A comparison is given below, in Fig. 1.

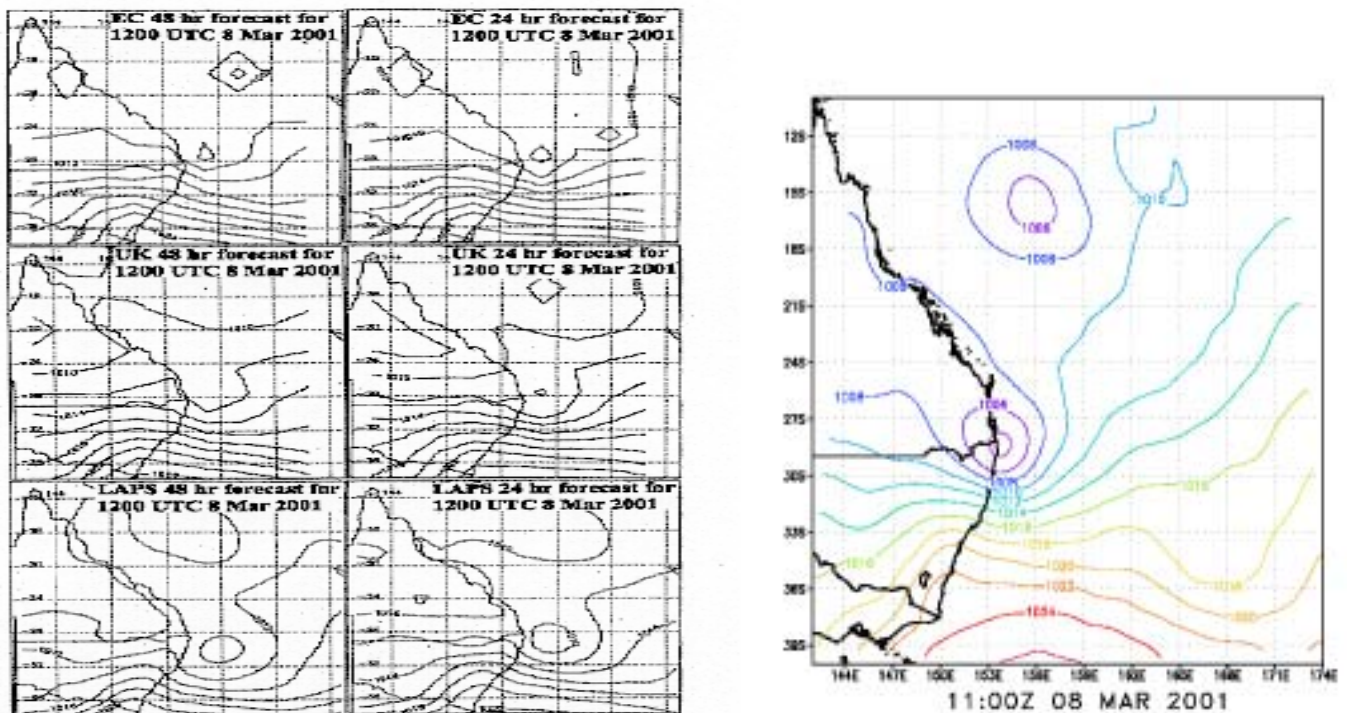


Figure 1: Left panel shows a selection of NWP model predictions, all of which fail to forecast landfall. Right panel shows the HIRES 48 hour prediction, with forecast landfall. HIRES landfall position and timing errors are 100km and 3 hours.

TC Structure – two approaches have been adopted in FY02. First, the major structural features of TCs must be identified and understood, from both observations and numerical simulations. Second, the HIRES system is being run at resolutions of 1km or less to provide simulations that are as realistic as possible to enable the fine structure of the TC to be simulated. The Atlantic and northwest Pacific basins have been targeted for FY02 and a number of model runs have been made for a current total of 7 TCs. Preliminary assessment of the results is highly encouraging but there remains considerable model verification yet to be carried out. The main tools for very high resolution verification are radar and other land-based instruments.

TC intensity and intensity change – preliminary work in FY01 using an adjoint sensitivity approach is being extended in FY02 to assess the capacity of NWP systems to forecast intensity and intensity change. This work is complementing the TC predictability research already completed. A graduate student employed under the grant is applying the adjoint sensitivity approach to landfalling TCs in the Atlantic basin, with some early indications of significant findings, especially in the Gulf of Mexico. Again, this work will be presented at the 2003 AMS Annual Meeting.

IMPACT/APPLICATIONS

My work has yielded a number of impacts/applications. First, I have further underlined earlier work, funded by ONR, which showed that TC track forecast errors are still far larger than acceptable. I estimate that the current levels of TC track prediction is still approximately twice as large as that which can ultimately expected to be achieved. A positive aspect of such a large gap between practice and theoretical limits is the possibility for improvement. Reducing track forecast errors most likely will come from improving the current inadequate specification of the initial state and also from the reductions in significant model deficiencies. A second impact I have confirmed in work carried out in FY02 is that careful quality controlled, high resolution, data from existing and new sources; developments in continuous (4D) assimilation; and ongoing model improvements will continue to yield large reductions in track forecast errors, especially for “difficult” TCs and for TCs nearing or making landfall. Third, I have confirmed tentative FY01 findings that realistic intensity forecasts are greatly enhanced by high NWP model resolutions of 5km or below. It is now becoming routine to obtain TC simulations that have many of the observed features of actual TCs, a situation that was novel just a few years ago. This further confirms my conclusions of FY00 and FY01 that the prediction of TC tracks and intensities is continuing to move within the reach of the emerging data observing systems, advanced assimilation schemes and the more sophisticated NWP models running at very high resolutions. Fourth, the adjoint sensitivity techniques developed in the previous proposal continue to produce reductions in mean TC track errors and have also improved our understanding of and capacity to predict TC structure, intensity, and intensity change. Fifth, it has been shown that existing methods for assessing NWP model performance are too crude and are biased in favor of the NWP model systems. New techniques that are far more exacting should be developed and applied to the NWP model output. These new methods are in the early stages of development, but must be incorporated into the suite of assessment procedures for routine testing, as soon as possible. Sixth, and finally, new precursors of TC activity and intensity have been identified, initially in the east Indian Ocean, to the northwest of Australia. Precursors are now being sought in the west Indian Ocean. These precursors exist at the inter-seasonal level down through the intra-seasonal level, to time-scales of days. New precursors of TC track and intensity have been identified during the life-cycles of particular storms.

RELATED PROJECTS

I have continued close links with other ONR programs, notably the CBLAST program on which I am co-PI on one proposal with Dr Michael Banner of The University of New South Wales. The CBLAST proposal is entitled “The Impact of Air-Sea Interaction Research on Larger-Scale Geophysical Flows.” I am also interacting with Dr Wang Yuqing, University of Hawaii, on the inclusion and impact of cloud microphysics schemes.

SUMMARY

The work being carried out in this proposal is aimed at increasing our knowledge base of tropical cyclones in a number of areas. Tropical cyclones, which are also referred to as hurricanes and typhoons, are the most devastating storms on earth. As such it is vital to understand and to predict their behavior. To do so in an accurate and timely manner requires research on their motion, their structure, their intensity, especially when nearing land. To achieve these aims, a program of data collection and computer model simulations is being carried out, with the predictions being compared with observations of selected storms. Deficiencies in the initial data, the model formulation and the model predictions are then identified and research is carried out on improving these aspects. The ultimate goal, expressed as succinctly as possible, is the provision of accurate, timely and reliable model predictions of TC tracks and intensity, especially for storms that threaten coastlines. The ONR funded research program I am carrying will help, make the School of Meteorology, University of Oklahoma, an international focal point in tropical cyclone research.

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